

**1989 NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM**

**JOHN F. KENNEDY SPACE CENTER  
UNIVERSITY OF CENTRAL FLORIDA**

**LOW FLOW VORTEX SHEDDING FLOWMETER**

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## **ABSTRACT**

The purpose of the summer project was to continue a development project on a no moving parts vortex shedding flowmeter used for flow measurement of hypergols. The project involved the design and construction of a test loop to evaluate the meter for flow of Freon which simulates the hypergol fluids. Results were obtained on the output frequency characteristics of the flow meter as a function of flow rate. A family of flow meters for larger size lines and ranges of flow was sized based on the results of the tested meter.

## SUMMARY

Currently turbine type flow meters are used to meter the loading of hypergolics into the Space Shuttle Orbiter. Because of problems associated with refurbishment of these meters after each launch, NASA considered the development of a no moving internal parts vortex shedding flowmeter. The University of Florida developed such a flowmeter for 1/2 inch tubing. The objective of the current summer project was to test a modified version of the university prototype and to develop a family of vortex shedding flowmeters for larger line sizes and flow ranges.

In order to test the meter for flow of Freon, which is similar to hypergols, a flow test loop was designed and built. A series of tests were performed on the prototype to evaluate its output characteristics. An alternate pressure transducer was used when the one in the original design failed and could not be replaced or repaired in time. Results of the tests indicate a linear relationship between vortex shedding frequency, as indicated by counting pressure pulsations, and flow rate.

Results of the testing indicate promise for the use of this type of meter for the application mentioned previously. Difficulties were encountered in reliably counting frequencies which are addressed in the report. Recommendations are also made for improving the flow loop for larger flow rates.

Based on the test results obtained, projected characteristics of larger sized flow meters were determined and a 1 inch prototype was designed and is being fabricated for future testing.

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## 1.0 INTRODUCTION

### 1.1 PROJECT NEEDS.

During the loading of hypergolic fuels and oxidizers, flow meters are used to meter the amount of fluid. The current methods of metering these fluids involves turbine type meters and shuttle-ball type vortex shedding meters. One of the problems that occurs with these meters is that after each launch the meters have to be taken apart and refurbished then recalibrated. The reason for this process is that there are moving parts of the meters in contact with the flowing fluid. An illustration of a typical turbine meter is shown in Figure 1.1. The bushings and bearings of these meters are susceptible to wear especially during the purge phases of the fuel loading process when severe over speed of the rotor can occur due to gas flow through the lines. The process of refurbishment of the meters is quite costly due to the techniques required to handle the very toxic hypergols. It is estimated that a savings of about \$1000 per meter per launch can be made if the meters do not require this maintenance. The current project involves the development of a family of flow meters which have no moving parts subject to the problems mentioned previously. The next section describes the history of the project prior to the current period of study.

### 1.2 PROJECT HISTORY.

Several years ago the University of Florida was contracted by NASA to investigate alternative methods of flow measurement which involve no moving parts in the flow stream. The results of the study were presented in the Final Report for Flowmeter and Liquid Level Instrumentation Contract No. NAS 10-10932 dated April 15, 1985.(1) An extensive study of flow measuring techniques resulted in more detailed studies of the vortex shedding types of flow measurement. One of the techniques studied involved the use of fiber optics. The complexities of this method ruled it out as a viable solution. A method of measuring pressure pulses resulting

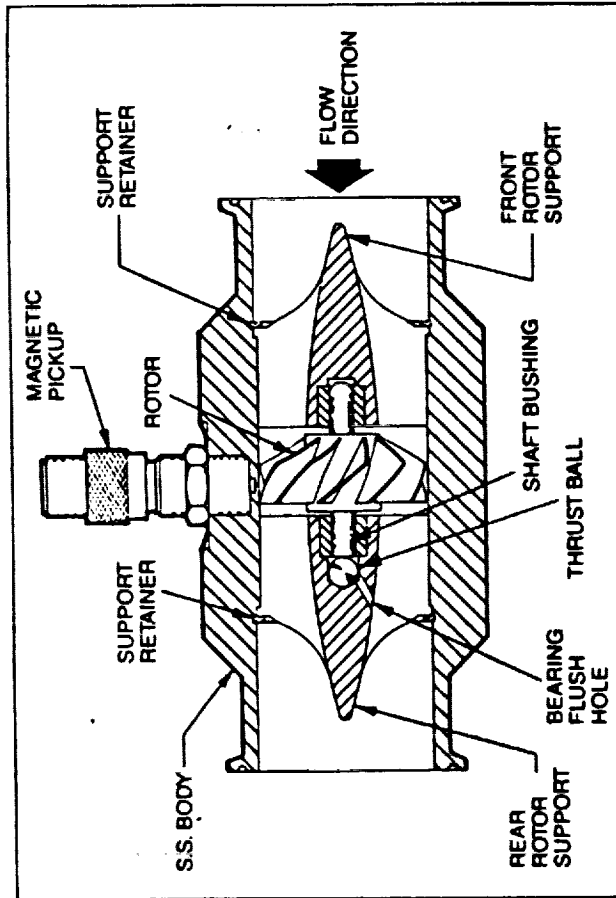


Figure 5: Turbine flowmeter consists of a multiple-bladed, free-spinning, permeable metal rotor housed in a non-magnetic stainless steel body. In operation, the rotating blades generate a frequency signal proportional to the liquid flow rate, which is sensed by the magnetic pickup and transferred to a read-out indicator.

Figure 1.1 Example of a Turbine Meter(Omega Engineering, Inc.)



from the vortex shedding phenomena was pursued and is described in Section 2 of this report.

## 2.0 BACKGROUND

### 2.1 VORTEX SHEDDING PHENOMENA.

The phenomena of vortices being shed from a surface in a flowing fluid is not new, and the application of this phenomena to the measurement of flowrate is well established. The 1985 NASA Final Report by the University of Florida (1) contains an extensive literature review of the use of vortex shedding in flow measurement. As a fluid flows over a surface placed in the flow stream vortices alternately spin off of the top and bottom surfaces of the body. This is illustrated in Figure 2.1. For a certain range of fluid velocities the rate or frequency of these vortices is linear with velocity. The relationship between vortex shedding frequency and velocity is contained in the definition of the Strouhal Number (2).

$$St = \frac{f \times d}{u} \quad \text{where}$$

$f$  = vortex frequency

$d$  = characteristic dimension

$u$  = fluid velocity

The equation can be rewritten in terms of flow rate and pipe size and is

$$St = \frac{f \times D^2 \times d}{4.90 \times Q} \quad \text{where}$$

$D$  = pipe diameter (inches)

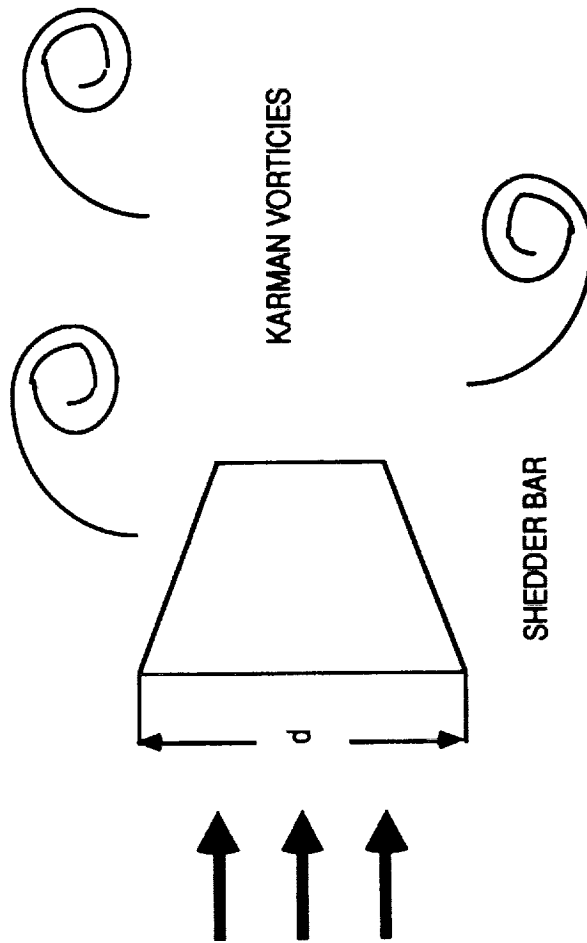


Figure 2.1 Vortex Shedding Phenomena

Q = flow rate (GPM)

d = characteristic dimension (inches)

f = frequency (Hz)

Current manufacturers of vortex shedding flow meters report a linear range of fluid velocities based on Reynold's Numbers in the range of 20,000 to 7,000,000 based on pipe diameter. The Reynolds number can be found using the following relationship.

$$Re = \frac{3160 \times Q \times G_t}{D \times CP} \quad \text{where}$$

Q = flow rate (GPM)

$G_t$  = specific gravity

D = pipe inside diameter (inches)

CP = viscosity (cp)

Ranges of Reynolds numbers for the flow meter considered in this project and for the predicted family of meters are presented in Section 4 of this report.

The geometry of the shedder bar determines the characteristic dimension of the shedder which then determines the frequency of vorticies. Several shapes of the shedder bar were studied by the University of Florida in determining the best shape for the flow meter developed. A description of this shedder is presented in the next section. The most common shedder bar shape is the reversed wedge shown in Figure 2.1.

There are several methods used to detect and measure the vortex frequency. Currently NASA uses Eastech vortex meters which incorporate a shuttle ball in the shedder bar which oscillates with the alternating vorticies. A reluctance pick up emits a pulse rate proportional to shuttle ball oscillation which then correlates to flow rate. Another method is illustrated in Figure 2.2 which shows vibration of the shedder bar sensed by a piezoelectric element. The

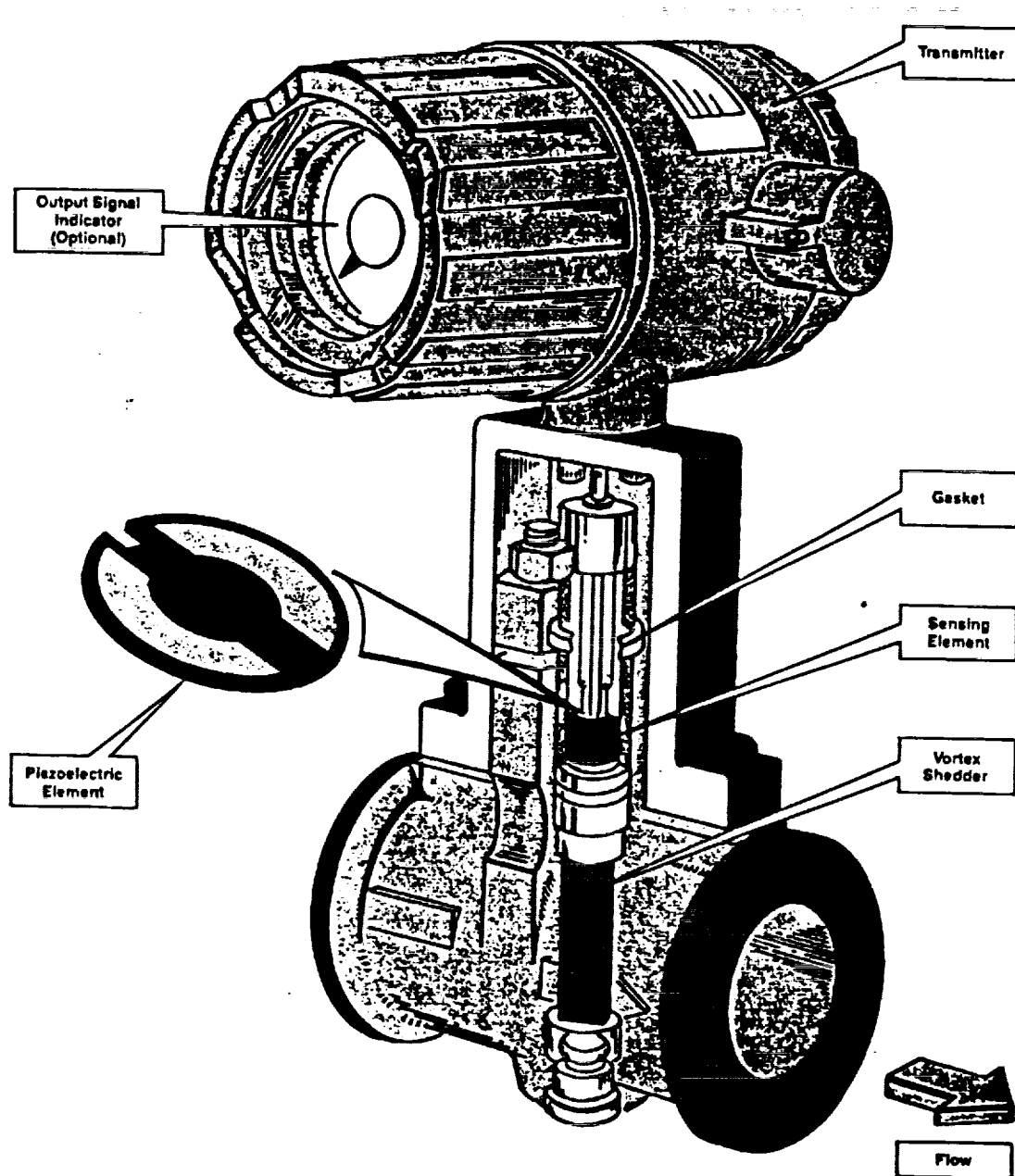


Figure 2.2 Example of a Vortex Shedding Flowmeter  
(Omega Engineering, Inc.)

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meter considered in this project uses a pressure transducer which detects pressure pulses associated with the vortices. A description of this meter is included in the next section.

## 2.2 UNIVERSITY OF FLORIDA DESIGN.

Upon completion of the alternative flow study by the University of Florida, the university was contracted by NASA to develop a working prototype vortex shedding flow meter. The details of the university project are described in the Final Report Vortex Shedder Flow Meter NASA Contract No. 10-11230 December 31, 1986 (4) and in a technical paper (5). Three prototypes of the meter developed are the basis for the study reported herein.

The university design resulted in a flow meter suitable for 1/2 inch tubing having a usable range of 1.5 to 15 GPM. There was considerable effort by the university to optimize various aspects of the flow meter design. The final design is shown in Figure 2.3. The shedder bar has a rectangular cross-section shown in Section B-B. Pressure pulses resulting from the vortices are transmitted through the three holes below the shedder bar to a cavity in which is placed a Kistler Model 206 pressure transducer. The pressure signal is then conditioned with a Kistler Model 5116 Coupler and then sent to a frequency counter and an oscilloscope. The university prototype has male flare tubing ends for insertion into the flow lines. An identical meter was constructed at KSC for testing purposes. Also, a modified meter was built at KSC which incorporates female boss threads in the meter body which accepts a boss to male flare tube adapter. This modification protects the meter body in case of male tubing thread damage which did occur to the university built prototype.

Extensive testing was done by the University of Florida on their design using water as the working fluid. A comparison of the published university results with the tests conducted in this project are presented in Section 3 of this report.

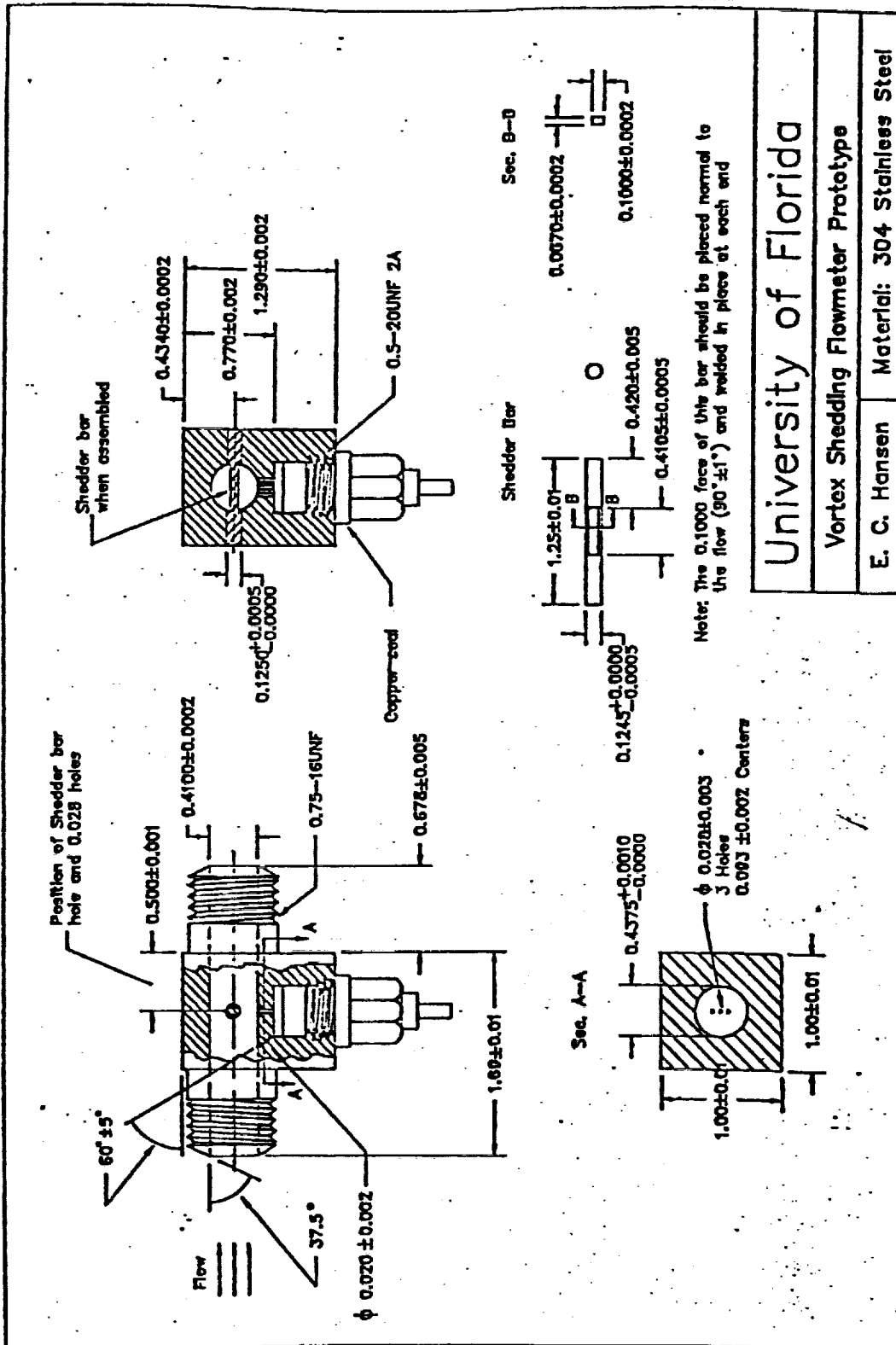


Figure 2.3 University of Florida 1/2 Inch Prototype

### 3.0 FLOW LOOP DESIGN AND TEST

#### 3.1 INTRODUCTION.

The basic goals of the current project were to design and construct a flow bench to test the University of Florida design and to determine the appropriate size flowmeters for larger flow values. The flow meter sizing is discussed in Section 4 of this report. The test considered in this section is on the KSC modified prototype which is similar to the U of Fla. model and involves Freon 113 (Trichlorotrifluoroethane) as the working fluid. Freon was chosen as it has similar properties to the hypergolic fluids which will be metered by the flowmeter considered in this project.

#### 3.2 FLOW BENCH DESIGN.

One of the goals of the summer project described in this report was to design and build a flow bench to test the 1/2 inch prototype flow meter. Due to the short time period involved, it was decided to utilize parts that were available on site. Pumps were the first consideration to circulate the fluid, however because of unavailable suitable pumps with desired pressure and flow characteristics an alternate method was selected. Results reported by the University of Florida indicated problems occurred when pressure upstream of the vortex meter dropped below certain levels causing what was thought to be cavitation. Since pressure was a factor, a source of gaseous nitrogen was used as the driving pressure for flow. A similar technique was done at NASA-Johnson for flow measurement.(6)

The flow loop which was designed and built is shown schematically in Figure 3.1. Initially two liquid nitrogen dewars were used as containers for the freon fluid. One dewar was located outside of the laboratory window and was connected to the flow loop through the window penetration indicated Dewar #2. The second dewar was located inside the lab and was placed on a load platform used to

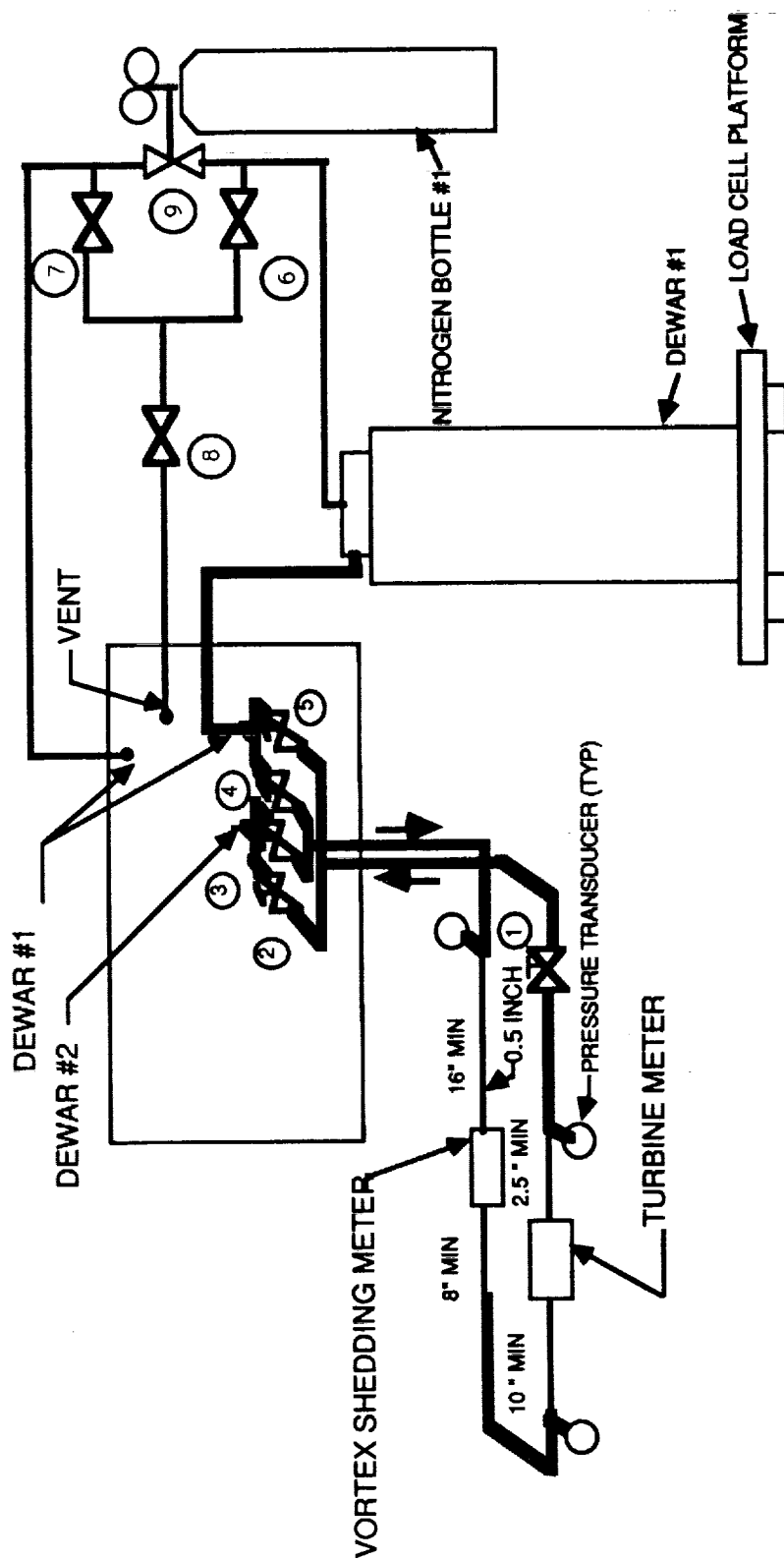


Figure 3.1 FLOW TEST SCHEMATIC



measure the weight change of the freon. By proper adjustment of the system valving fluid could flow through the loop from either dewar. If pumping from Dewar #1 to Dewar #2, Dewar #1 is pressurized with nitrogen gas and Dewar # 2 is vented as a receiver. A more detailed procedure is included in Section 3.3 and in the Appendix. The quantities measured in the loop include the outputs from the turbine meter used as a standard, from the vortex meter under test, from pressure transducers at various locations on the test loop, and from the load cell transducers located under Dewar #1. The vortex meter output signal is a pressure detected by a Kistler Model 206 pressure transducer as shown in Figure 2.3. The Kistler transducer is a piezoelectric type of device and comes with a signal coupler which produces an AC coupled millivolt output proportional to pressure fluctuations. During some of the modifications that were made to the prototypes the Kistler transducer was damaged beyond repair and could not be replaced before the conclusion of this summer project. As an interim solution to the problem of pressure measurement an Entran transducer was adapted to the flow meter to check out the flow loop. The Entran sensitivity was much less than that of the Kistler so considerable signal conditioning steps were taken to produce a measurable output. A schematic of the amplifier/filter circuit is shown in Figure 3.2. The basic experimental tests that were conducted are described in the following section.

### 3.3 FLOW METER TESTING.

The basic procedure used to produce the results obtained is outlined in more detail in the Appendix. Depending on whether flow was coming from Dewar #1 or Dewar #2 valves 2, 3, 4 and 5 were in the open or closed position.(See Figure 3.1) To vary the flow rate more or less pressure was applied to the full dewar using the three-way valve connected to Nitrogen Bottle #1. By opening gate valve #1 to the maximum open position allowing the flow rate to be governed by the nitrogen pressure. Steady flow was indicated by a steady output reading from the calibrated turbine meter in series with the

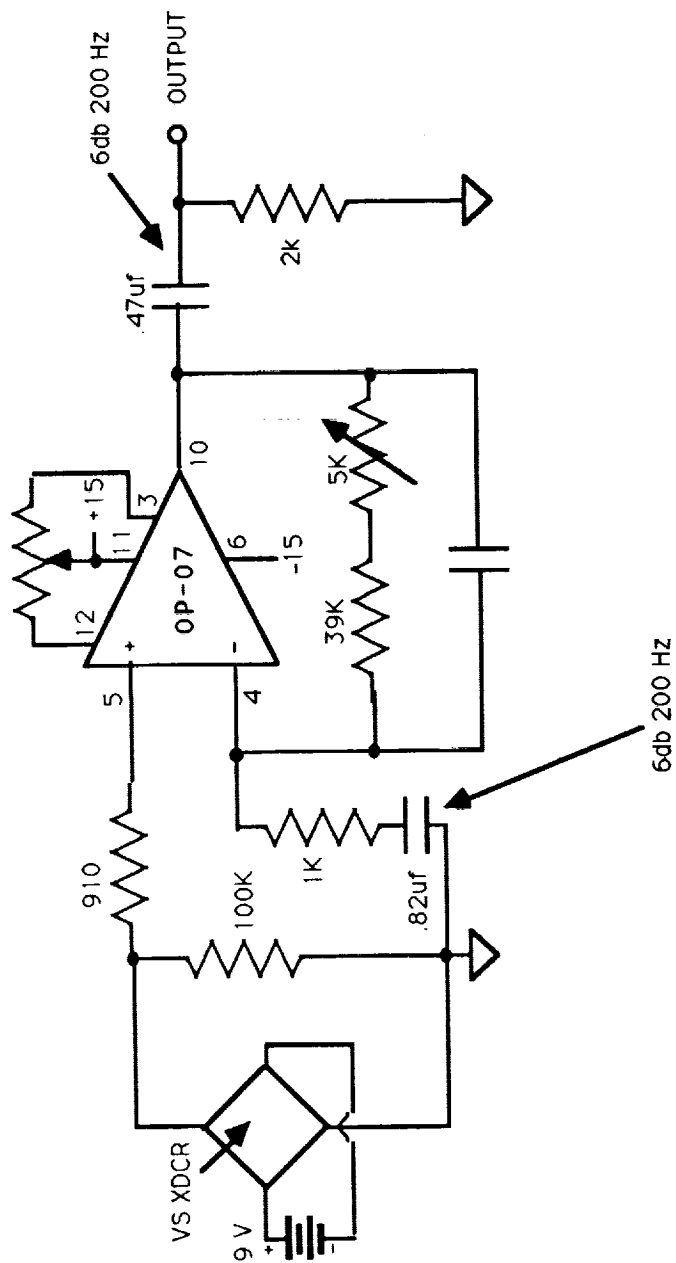


Figure 3.2 Signal Conditioning Amplifier for Temporary Pressure Transducer

vortex meter. The turbine meter output consists of a voltage from the signal conditioner which is linearly proportional to the flow rate. The calibration curve relating gallons per minute (GPM) to output voltage is presented in Figure 3.3. Calibration of the turbine meter was performed at the KSC flow calibration facility. Once the Dewar Load Platform data is incorporated into the data acquisition system, mass flow rate can be measured through an increase or decrease of the fluid in the dewar. As a rough check of the turbine output, a timed change in dewar weight was performed at one flow rate. Since load cell output was indicated at one pound increments determination of start time and stop time weights was susceptible to plus or minus one pound error on each of the three load cells. This uncertainty along with freon density uncertainty the result of this rough test compared favorably with the turbine meter output.

The output from the vortex shedding flow meter was measured using a frequency counter and an oscilloscope. Even with amplification, the output signal from the Entran pressure transducer was quite small although it was measurable with the frequency counter and visible on the oscilloscope. Up to 7 GPM the readings were consistent between the two methods, however above that flow rate flow noise or turbulence produced a wandering of the pressure pulsations which resulted in some pulses not being counted. Oscilloscope traces however could be counted and produced reasonable results. The oscilloscope used had a storage capability which permitted freezing of the trace for easier pulse counting and frequency determination. Recommendations concerning this problem are presented in Section 5.

A problem that was encountered using the inside-outside dewar system was a limited flow capacity of the system. The dewar bottles have a small liquid line size which placed a restriction on the system due to flow out of one and into another. With the maximum desirable pressure in the outflow dewar of 150 psi flow was limited to approximately 10 GPM. A test was performed which permitted flow directly from one dewar into the other without going through the flow loop. Flow was measured using a 3/4 inch

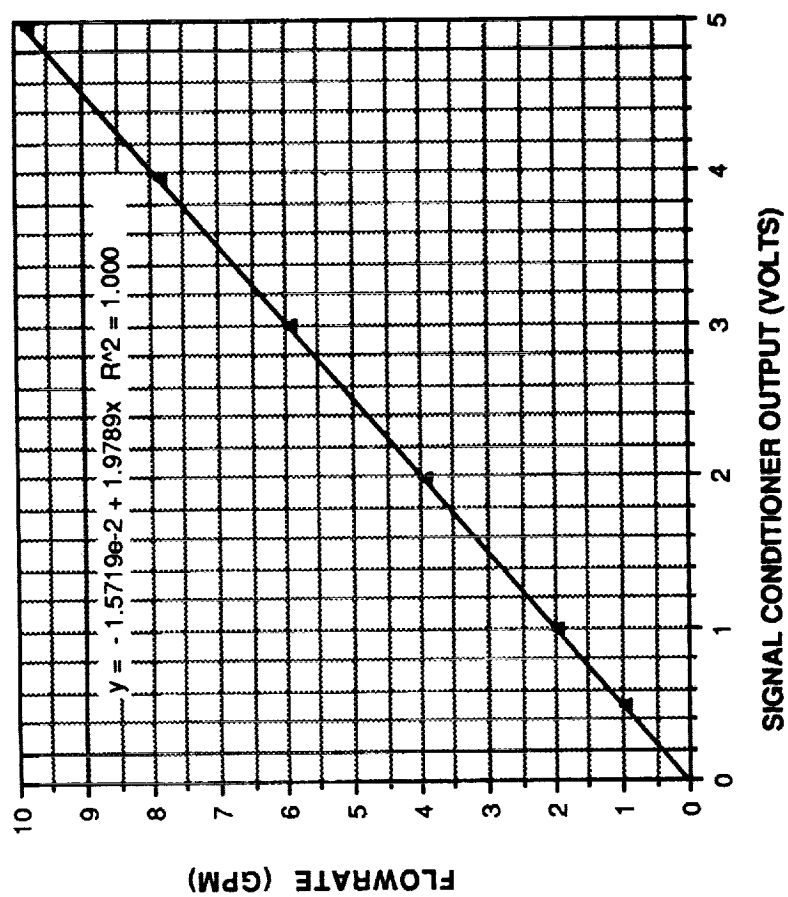


Figure 3.3 1/2 Inch Turbine Meter  
Calibration Results

calibrated turbine meter and was found to be not much more than the maximum found through the loop. In an attempt to increase the flow capacity, the outside dewar was brought inside and connected in parallel with the inside dewar. The outflow from the system was put into a vented 55 gallon drum which was placed outside. To refill the dewars the fluid was forced back inside using a small pressure applied to the drum. This limits the flow to one direction only, however even with the small driving pressure on the drum, flow could be circulated through the loop at a rate of 4 GPM. With the two dewars in parallel a flow rate of 12.5 GPM was achieved. Suggestions to improve the flow capacity are presented in Section 5.

Another test performed involved the measurement of pressure drops through the flow loop at higher flow rates. At a flow rate of approximately 11.5 GPM a pressure drop of about 36 psi occurred through the 1/2 inch tubing including the vortex meter. Reduction of the length of 1/2 inch tubing upstream and downstream of the vortex meter will help. Also a similar pressure drop occurred through the turbine meter and associated 1/2 inch tubing. This can be reduced by using the 3/4 inch meter and tubing.

### 3.4 RESULTS AND DISCUSSION.

The experimental results consists of a determination of vortex shedding frequency versus flow rate which is shown in Figure 3.4. As can be seen from the diagram, the relationship between vortex frequency and flow rate is linear. There is some scatter of the data at flow rates above six gpm which can be attributed to the method of determining the frequency by pulse counting an oscilloscope trace as discussed previously. The pressure signal produced from the Entran transducer required considerable amplification and filtering to make it measurable. At that, the output was very repeatable at lower flow rates where it could be counted reliably using a frequency counter. It is anticipated that the Kistler pressure transducer will produce a better output signal due to its greater sensitivity.

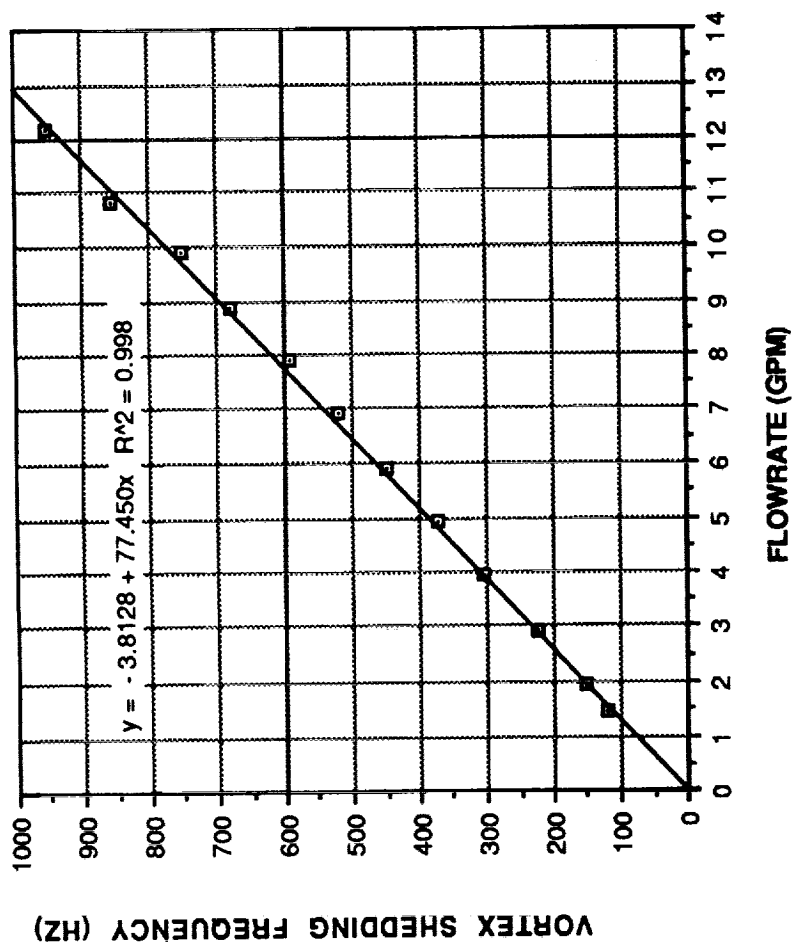


Figure 3.4 Test Results for KSC Modified  
1/2 Inch Vortex Shedding Flowmeter Using  
Freon

Data from the tests performed by the University of Florida was plotted and is shown on Figure 3.5. The results also show a linear relationship between vortex frequency and flow rate. The university results are for water as the flowing medium. Table 3.1 shows a comparison of results from the university tests and those done under this project. A similar range of flow rates was used in both studies producing similar velocities. The Reynolds numbers involved were higher for the Freon test due to the increased density of Freon compared to water and due to the lower viscosity of Freon. The importance of this higher Reynolds number for a given velocity is that the useful range of vortex shedding can be extended since it is tied to a lower allowable value of Reynolds number.(3,1) A further discussion of this is found in Section 4 concerning vortex meters for larger flow rates. Another difference between the university results and those from the KSC test involved the Strouhal Number. In Section 2.1 it was shown that the dimensionless Strouhal number is proportional to vortex shedding frequency and characteristic dimension and is inversely proportional to fluid velocity. The university results have a Strouhal number less than that of the KSC results. In both cases the values of the Strouhal numbers are constant, again indicating the linear relationship between frequency and flow rate. It is not known why there is a difference in Strouhal numbers, however the tests were conducted on different meters and involved different fluids. The important point is that in either case the Strouhal number is a constant which permits a count of vortex frequency to be a linear measure of flow rate.

#### 4.0 FLOW METER SIZING FOR LARGER FLOWS

The geometry of the shedder bar in a vortex shedding meter is related to the inside diameter of the pipe. It has been found empirically that the ratio of characteristic dimension,  $A$ , to pipe diameter,  $D$ , should be in the range of 0.15 to 0.40(1). The university design uses an  $A/D$  ratio of 0.24. Also the ratio of the shedder bar dimension in line with the flow,  $B$ , to the characteristic dimension should be in the range of 1.0 to 2.0. The university design for this ratio is  $B/A = 0.67$ . Holding these ratios constant and using the

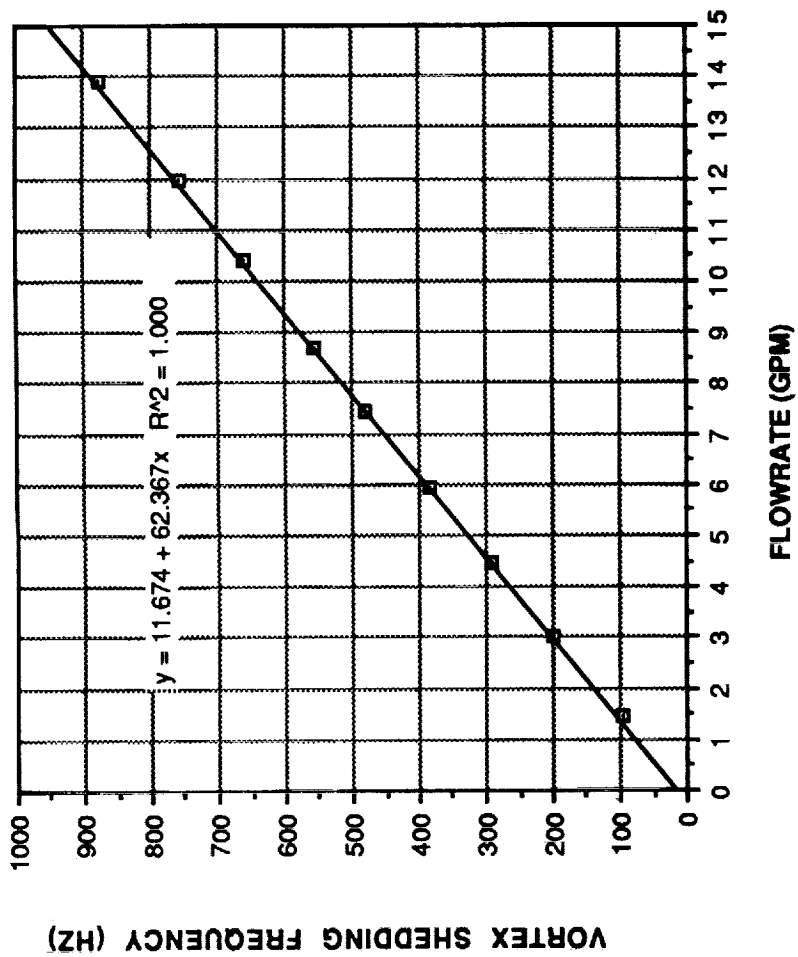


Figure 3.5 Test Results for 1/2 Inch Vortex Shedding Flow Meter Using Water (Univ of Florida)



Table 3.1 Comparison of Test Results of University of Florida  
and KSC Modified Prototype Vortex Flowmeters

	UNIV FLA PROTOTYPE	KSC MODIFIED PROTOTYPE
TYPE OF FLUID	WATER	FREON 113 (TRICHLOROFLUOROETHANE)
RANGE OF FLOW (GPM)	1.5 - 13.9	1.5 - 12.2
RANGE OF VORTEX SHEDDING FREQUENCIES (HZ)	97 - 876	112 - 952
RANGE OF REYNOLDS NUMBERS	11,600 - 107,000	26,600 - 525,000
RANGE OF FLUID VELOCITIES (FT/SEC)	3.6 - 33.8	3.6 - 29.6
AVERAGE STROUHAL NUMBER	0.22	0.26

inside diameters for larger size tubing a table of flow meter properties for larger sizes is shown in Table 4.1. The table shows the anticipated flow range for several sizes larger than 1/2 inch. Also the scaled shedder bar size is indicated along with the projected vortex shedding frequency range. The frequency range is based on a Strouhal number of 0.26 which was found experimentally for the modified KSC prototype. The range of velocities and Reynolds numbers for Freon are included. Because the velocity range for all of the sizes considered is essentially the same, the fact that the characteristic dimension for the larger size meters is also larger results in a smaller range of vortex shedding frequencies. This does not present any difficulty in the counting of the frequencies, however it does mean that the measured frequency is closer to extraneous noise such as flow turbulence associated with piping fittings and also with electrical noise affecting the output signal. A further discussion of this is in Section 5.

A flow meter for a 1 inch application was designed and is shown in Figure 4.1. The meter is scaled up from the modified KSC prototype design which has internal boss thread on the meter body to accept boss to flare tubing end connections. The meter uses the same pressure transducer as that used in the 1/2 inch model. A prototype of this meter is currently being fabricated at KSC however it will be tested after this phase of the project is completed. The new prototype will be made from aluminum to ease in the construction however the final design will be stainless steel. The 1/2 inch meter has a hole drilled at an angle from the front of the pressure sensor port into the flow path.(See Figure 2.3) This hole was incorporated by the university to aid in purging trapped air from the pressure transducer port. The 1 inch design does not have this angled hole, for the purpose of determining whether it is really required. If necessary it can be readily added. Another modification to the meter design which would allow investigation of the orientation of the shedder bar would be to flute the .250 inch round part of the shedder bar and also the hole through the meter body. This will allow rotation of the shedder bar within the flow stream. A means

Table 4.1 Projected Vortex Shedding Flowmeter Characteristics

	1/2 "	3/4 "	1 "	1 1/2 "	2 "
	D = 0.410	D = 0.609	D = 0.844	D = 1.312	D = 1.781
FLOW RANGE (GPM)	1.0 - 10.0	2.5 - 25.0	6.0 - 60.0	15.0 - 150.0	32.0 - 320.0
SHEDDER BAR SIZE (INCHES)	.100 x .067	.149 x .100	.206 x .138	.320 x .214	.435 x .291
VORTEX FREQUENCY RANGE (HZ) BASED ON ST = 0.26	76 - 758	58 - 576	52 - 520	35 - 347	30 - 295
VELOCITY RANGE (FT/SEC)	3.6 - 36.5	2.8 - 27.5	3.4 - 34.4	3.6 - 35.6	4.1 - 41.2
REYNOLDS NUMBER RANGE	26,600 - 266,000	29,900 - 299,000	51,700 - 517,000	83,200 - 832,000	131,000 - 1,310,000

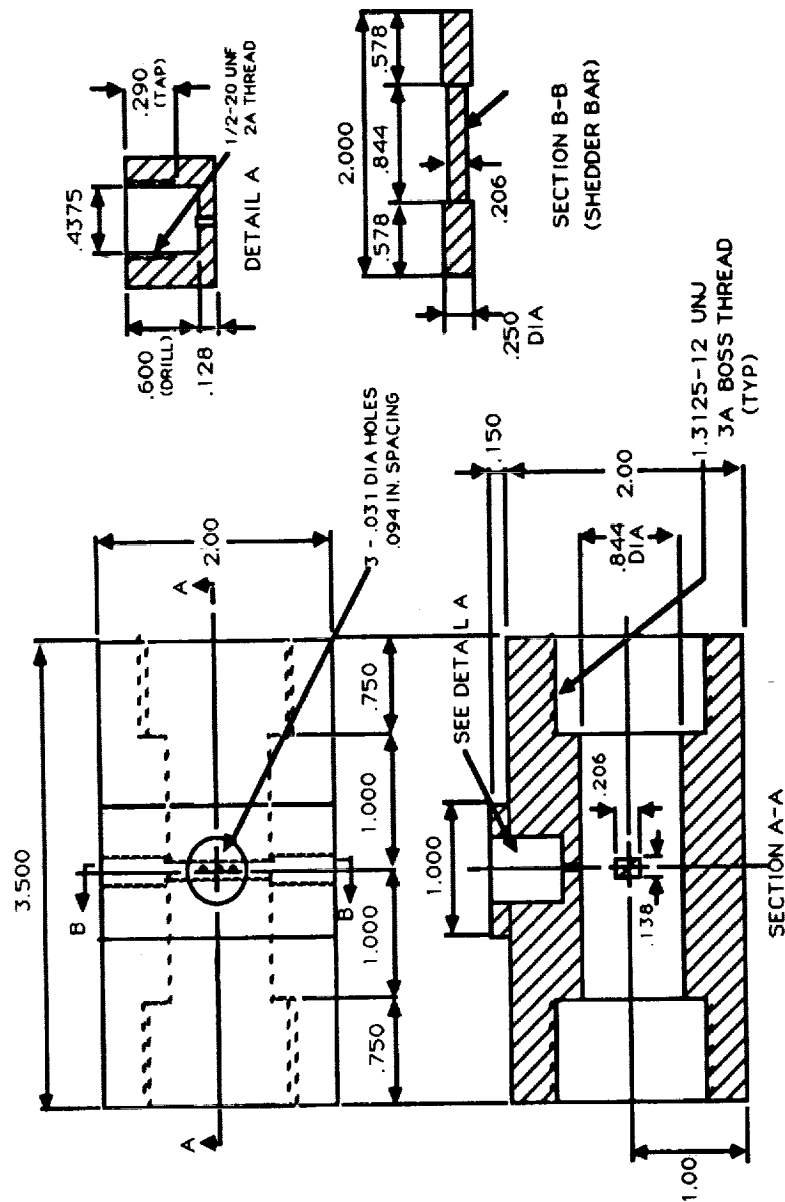


Figure 4.1 One Inch Vortex Shedding Flowmeter Prototype

of sealing the bar will be necessary such as recessing the shedder bar in the meter body and providing a sealed plug on the outside of each side. To test the 1 inch meter in the existing flow loop only the lower end of the 6 - 60 gpm flow range can be achieved. Some modifications to improve flow capacity are discussed in Section 5.

## 5.0 CONCLUSIONS

A few conclusions can be drawn as a result of the preliminary tests conducted on the KSC modified vortex shedding flowmeter prototype. These conclusions are generally in the form of recommendations for further study for the project.

Since the test data obtained for this project was for a flowmeter outfitted with a temporary pressure transducer in place of the Kistler Model 206, final judgement on the functionality of the meter should wait until tests can be run on the flowmeter with the Kistler installed. A similar set of flow rates can be achieved with the test flow loop as outlined in Section 3.3 and in the Appendix. Based on a preliminary test involving the Kistler transducer, the output should be much stronger than that from the Entran sensor which will result in better signal conditioning results.

Another difficulty encountered in the tests of this study involved flow noise in the forms of turbulence caused by line fittings and low frequency static pressure changes. Both of these occurrences resulted in missed counts by the frequency counter. Overcoming this is critical to the use of this flowmeter due to the frequency being a measure of the flow rate. As part of the suggested solution a spectrum analysis of the output signal can be made which will identify frequency components of the signal. Hopefully the largest frequency component will be the vortex shedding frequency and the remaining frequencies will be noise. A first attempt at noise elimination should be through electronic filtering of the output signal. This may involve filters for each flowmeter size due to the different ranges of vortex shedding frequencies. Other solutions may involve flow line modifications. Restrictions on meter

placement in the actual application may affect this solution. Flow line remedies may include some form of fluid accumulator similar to the one placed on the flow loop. Preliminary tests with this accumulator showed some promise in removal of some flow noise. Also, the use of flow straighteners in the meter body may improve the situation.

Some recommendations concerning the constructed flow loop are in order. As mentioned previously the loop was designed using available components rather than optimum ones. For a more permanent design certain parts should be changed. The two tank system with nitrogen gas as the driving force worked very well, however the restriction to flow rate placed on the system by the nitrogen dewars is too great. For flow rates larger than 15 gpm different tanks should be used. Tanks could be constructed capable of 200 psi internal pressure which have sufficient volume and flow inlet and outlet line sizes to permit the desired flow rate. Immediate solutions to the existing flow restriction problem involve the elimination of all 1/2 inch lines including upstream and downstream of the vortex meter, and replacement of the 1/2 inch turbine meter with a 3/4 inch meter which is calibrated over the range 1.5 - 32 gpm. The arrangement of the dewars into a parallel output arrangement helps to increase the capacity of the current system and should be used as such. More Freon should be ordered, and the outside storage drums should be connected in parallel for collection of the additional fluid.

A data acquisition system is proposed for the flow test loop. A Macintosh II computer using Labview software will monitor and analyze data from the loop. This will permit the recording and analysis of several simultaneous pieces of information from the loop including turbine meter output (voltage proportional to flow rate), vortex frequency count, pressures throughout the system (voltage proportional to psi), and change in dewar weight (voltage proportional to load or weight). The Labview software will permit plotting of results and perhaps frequency spectrum analysis.

A vortex shedding flowmeter which senses pressure pulsations produced by vortices appears to be a viable solution to the no moving parts flowmeter. Further testing will determine whether the output signal count will present major problems.

## APPENDIX

### DATA TABLES

#### Data for KSC Prototype Test

Flow Rate GPM	Vortex Frequency HZ	Tank Press psi
1.460	120	xxxx
1.960	153	xxxx
2.950	226	xxxx
3.940	304	16.5
4.930	373	26.4
5.920	450	38.1
6.910	521	58.5
7.900	591	66.0
8.890	682	75.0
9.880	750	96.0
10.810	854	108.0
12.200	952	138.0

### TEST PROCEDURES

Flow Out of Dewar #1 Into Dewar #2 Governed By Tank Pressure  
Refer to Figure 3.1 in Section 3.2

1. Fill Dewar #1
2. Close all valves.
3. Open valves 1, 2, 7 and 8.
4. Open three way valve #9 to apply pressure to Dewar #1.
5. Adjust regulator on nitrogen bottle to desired tank pressure. See



data table above for approximate governing pressure for a given flow rate.

6. Open valve 4 to commence flow. Regulator valve can be adjusted to increase flow rate and vent valve 6 can be opened to decrease flow.
7. Steady flow is achieved when output voltage from turbine meter signal conditioner is constant.
8. Record sensor outputs and frequency counter output.
9. Close valve 4 to stop flow.
10. If additional fluid remains in Dewar #1 to run another flow rate, repeat steps 5 to 9. otherwise follow next procedure.

#### Flow Out of Dewar #2 Into Dewar #1

1. Close all valves.
2. Open valves 1, 5, 6, and 8.
3. Open three way valve 9 to apply pressure to Dewar #2.
4. Adjust regulator to desired tank pressure.
5. Open valve 3 to begin flow. Increase flow with regulator, decrease by opening vent valve 7.
6. Repeat steps 7 and 8 above.
7. Close valve 3 to stop flow.

#### Flow Out of Two Dewars in Parallel

1. With both dewars full close all valves.
2. Repeat steps 3 to 9 from Dewar #1 to Dewar #2 procedure.
3. When all fluid is out of the dewars refill from outside storage drums.

#### Flow From Storage Drums Into Dewars

1. Close all valves.
2. Open three way valve 9 to apply pressure to the storage drum.

Use no more than 20 psi on the drum.

3. Open valves 6 and 8 to vent dewars.

4. Once dewars have reached atmospheric pressure open valves 2 and 5 to begin the flow from the drum into the dewars. Flow can be directed through the flow loop by opening valves 1, 3, and 5 instead of 2 and 5.

3. Close all valves when dewars have been filled.

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